



# Overview of Additive Manufacturing Initiatives at NASA Marshall Space Flight Center

Airbus  
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# Contributors

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- Andrew Owens: NASA Tech Fellow, MIT PhD Candidate
- Mike Snyder: Made In Space, Chief Designer
- Omar Mireles: NASA MSFC Engine Systems Design/Additive Manufacturing Designer
- Daniel Cavender: NASA MSFC Liquid Propulsion Systems Design; Small Thrusters
- Paul Gradl: NASA MSFC Liquid Engine Component Development and Technology, Lead, Nozzles
- Andy Hardin: NASA MSFC SLS Liquid Engines Office
- Dr. Doug Wells: NASA MSFC Lead, Additively Manufactured Space Flight Hardware Standard and Specification
- Brad Bullard: NASA MSFC Lead, Additive Injectors
- Sandy Elam Greene: NASA MSFC Lead, Additive Injectors
- Chris Protz, NASA MSFC Lead, Additive Combustion Chamber
- Jim Richard: NASA MSFC Lead, Additively Manufactured Valves
- Dave Eddleman: NASA MSFC Lead, Additively Manufactured Valves
- Travis Davis: NASA MSFC Lead, Additively Manufactured Valves
- Derek O'Neal: NASA MSFC Lead, Liquid Oxygen Pump
- Marty Calvert: NASA MSFC Lead, Turbopump

# Agenda

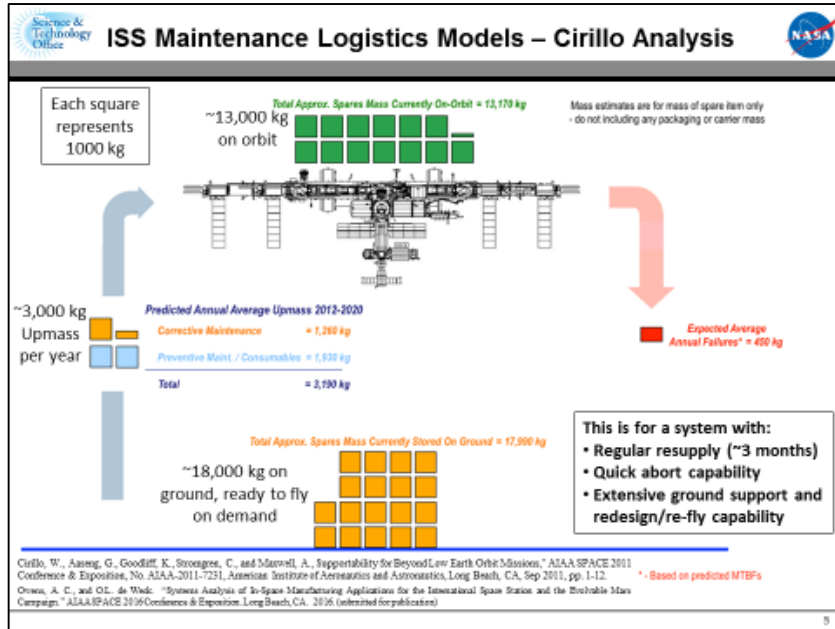
## **NASA's In Space Manufacturing Initiative (ISM)**

- The Case for ISM: WHY
- ISM Path to Exploration
  - Results from 3D Printing in ZeroG Technology Demonstration Mission
  - ISM Challenges
- In Space Robotic Manufacturing and Assembly (IRMA)
- Additive Construction

## **Additively Manufacturing (AM) Development For Liquid Rocket Engine Space Flight Hardware**

## **MSFC Standard and Specification For Additively Manufactured Space Flight Hardware**

## **Summary**

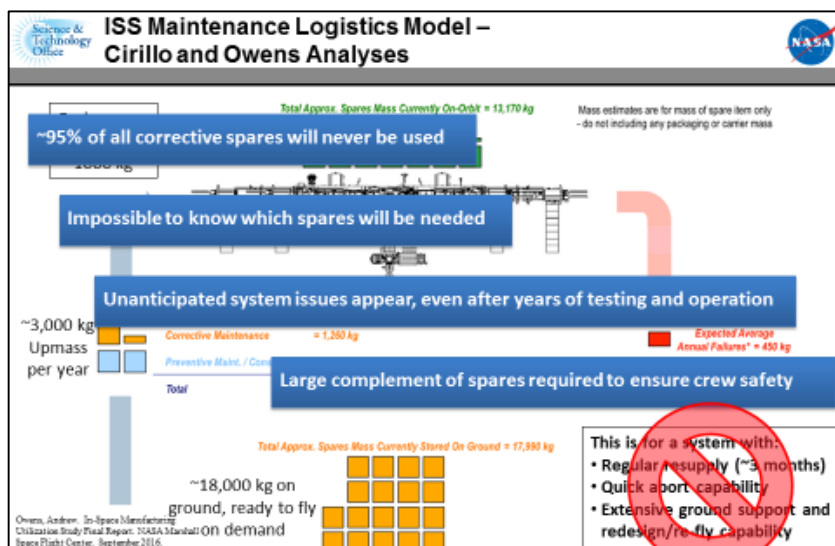


Current maintenance logistics strategy **will not be effective** for deep space exploration missions

## Benefits from Incorporation of ISM

ISM offers the potential to:

- Significantly reduce maintenance logistics mass requirements
- Enable the use of recycled materials and in-situ resources for more dramatic reductions in mass requirements
- Enable flexibility, giving systems a broad capability to adapt to unanticipated circumstances
- Mitigate risks that are not covered by current approaches to maintainability







# In-Space Manufacturing (ISM) Path to Exploration



## GROUND-BASED

### Earth-Based Platform

- Certification & Inspection Process
- Design Properties Database
- Additive Manufacturing Automation
- Ground-based Technology Maturation & Demonstration
- **AM for Exploration Support Systems (e.g. ECLSS) Design, Development & Test**
- **Additive Construction**
- **Regolith (Feedstock)**

## EARTH RELIANT ISS

### ISS Test-bed – Transition to Deep Space Gateway

- 3D Print Demo
- Additive Manufacturing Facility
- In-space Recycling
- In-space Metals
- Printable Electronics
- Multi-material Fab Lab
- In-line NDE
- **External Manufacturing (IRMA)**
- **On-demand Parts Catalogue**
- **Exploration Systems Demonstration and Operational Validation**

## CIS-LUNAR

## EARTH INDEPENDENT Mars

### Planetary Surfaces Platform

- **Multi-materials Fab Lab (metals, polymers, automation, printable electronics)**
- **Food/Medical Grade Polymer Printing & Recycling**
- **Additive Construction Technologies**
- **Regolith Materials – Feedstock**

*Text Color Legend*

Foundational AM Technologies

**AM Capabilities for Exploration Systems**

**Surface / ISRU Systems**

# Key ISM Thrust Areas





# The First Step: The 3D Printing in Zero G Technology Demonstration Mission



The 3DP in Zero G Tech Demo delivered the first 3D printer to ISS and investigated the effects of consistent microgravity on fused deposition modeling

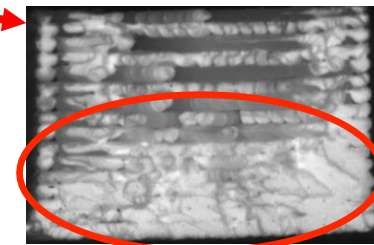
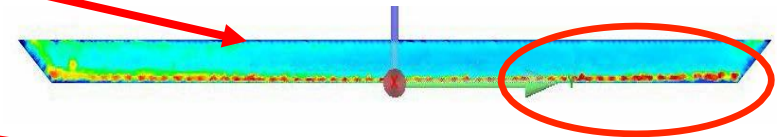
**Phase I Prints (Nov-Dec 2014):** mechanical property test articles; range coupons; and functional tools



Printer inside Microgravity Science Glovebox (MSG)

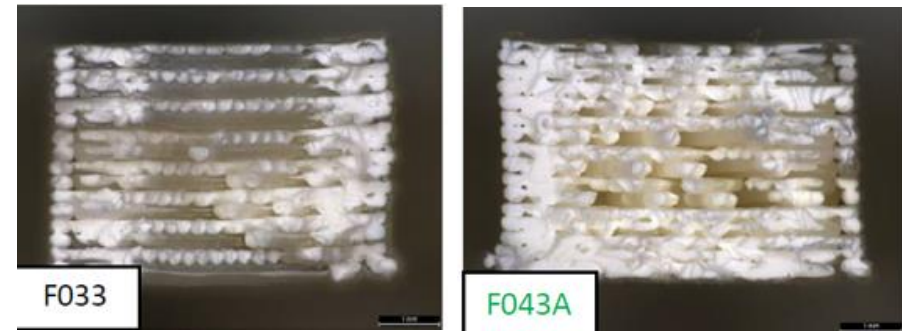
## Key Observations:

- Tensile and Flexure: Flight specimens stronger and stiffer than ground specimens
- Compression: Flight specimens are weaker than ground specimens
- Density: Flight specimens slightly more dense than ground specimens; compression specimens show opposite trend
- Structured Light Scanning: Protrusions along bottom edges (more pronounced for flight prints)
- Microscopy: Greater Densification of Bottom Layers (flight tensile and flexure)
- Z-Calibration distance variation suspected to be primary factor driving differences between flight and ground samples
- Potential influence of feedstock aging are being evaluated further



# Key Results: The 3D Printing in Zero G Technology Demonstration Mission (Phase II)

- Phase II Prints:
  - 25 specimens (tensile + compression) built at an optimal extruder standoff distance.
  - 9 specimens printed with intentionally decreased extruder standoff distance to mimic Phase I flight process conditions
- Key findings:
  - No substantive chemical changes in feedstock
  - No evidence of microgravity effects noted in SEM, SLS, CT analysis. Some internal structure variation between builds and with changes in process settings (primarily compression)
  - All prints to date with 3DP appear to be broadly part of the same family of data
  - Phase I data variations appear traceable to:
    - Differences in manufacturing process settings (extruder standoff distance)
    - Data scatter characteristic of many additively manufactured materials and processes.
    - Printer variability



Cross-section of PII tensile specimen manufactured at optimal extruder setting (left) compared with specimen manufactured at a reduced extruder standoff distance (right). Right image has a cross-section characteristic with PI flight prints.

Specimen set	Average ultimate tensile strength (KSI)	Coefficient of variation
Phase II	3.68	6.71
Phase II optimal	3.63	6.61
Phase II off-suboptimal	3.93	0.07
Phase I ground	3.46	1.71
Phase I flight	4.04	5.95

**Overall, we cannot attribute any of the observations to microgravity effects.**





The Made in Space Additive Manufacturing Facility (AMF)

- Additive Manufacturing Facility (AMF) is the second generation printer developed by Made in Space, Inc.
- AMF is a commercial, multi-user facility capable of printing ABS, ULTEM, and HDPE.
- To date, NASA has printed several functional parts for ISS using AMF



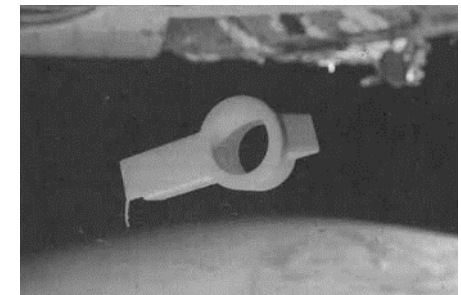
**SPHERES Tow Hitch:** SPHERES consists of 3 free-flying satellites on-board ISS. Tow hitch joins two of the SPHERES satellites together during flight. Printed 2/21/17.



**REM Shield Enclosure:** Enclosure for radiation monitors inside Bigelow Expandable Activity Module (BEAM). Printed 3/20/17 (1 of 3).



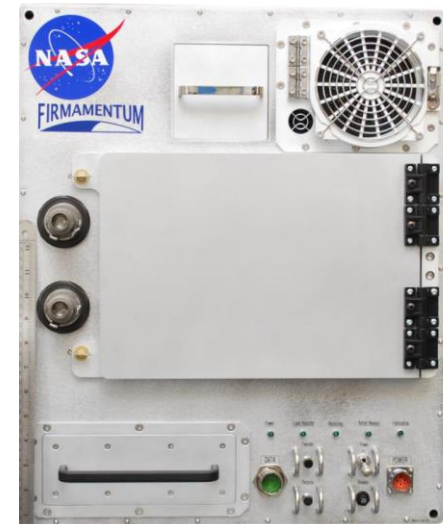
**Antenna Feed Horn:** collaboration between NASA Chief Scientist & Chief Technologist for Space Communications and Navigation, ISM & Sciperio, Inc. Printed 3/9/17 and returned on SpaceX-10 3/20/17.



**OGS Adapter:** adapter attaches over the OGS air outlet and fixtures the velocicalc probe in the optimal location to obtain a consistent and accurate reading of airflow through the port. 7/19/2016.

# ReFabricator from Tethers Unlimited, Inc.: Closing the Manufacturing Loop

- Technology Demonstration Mission payload conducted under a Phase III SBIR with Tethers Unlimited, Inc.
- Refabricator demonstrates feasibility of plastic recycling in a microgravity environment for long duration missions
  - Closure of the manufacturing loop for FDM has implications for reclamation of waste material into useful feedstock both in-space and on-earth
- Refabricator is an integrated 3D printer (FDM) and recycler
  - Recycles 3D printed plastic (ULTEM 9085) into filament feedstock through the Positrusion process
- Environmental testing of engineering test unit completed at MSFC in April
  - Payload CDR completed in mid-June
  - Operational on ISS in 2018

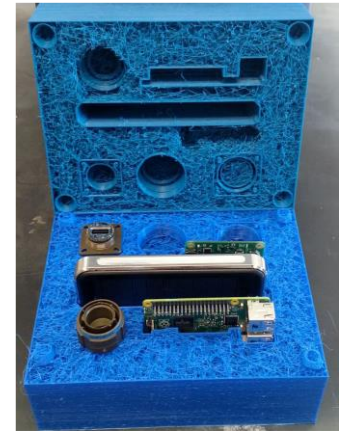


Refabricator ETU



Prater, Tracie, et al. "NASA's In-space Manufacturing Project: Materials and Manufacturing Process Development Update." Proceedings of the National Space and Missile Materials Symposium. June 2017.

- Logistics analyses show the dramatic impact of a recycling capability for reducing initial launch mass requirements for long duration missions
  - Current packaging materials for ISS represent a broad spectrum of polymers: LDPE, HDPE, PET, Nylon, PVC
- Tethers CRISSP (Customizable Recyclable ISS Packaging) seeks to develop common use materials (which are designed to be recycled and repurposed) for launch packaging
  - Work under Phase II SBIR
  - Recyclable foam packaging made from thermoplastic materials using FDM
  - Can create custom infill profiles for the foam to yield specific vibration characteristics or mechanical properties
- Cornerstone Research Group (CRG) is working under a Phase II SBIR on development of reversible copolymer materials
  - Designs have strength and modulus values comparable to or exceeding base thermoplastic materials while maintaining depressed viscosity that makes them compatible with FDM



CRISSP (image from Tethers Unlimited)



FDM prints using reclaimed anti-static bagging film with reversible cross-linking additive (image from Cornerstone Research Group)

- Made in Space Vulcan unit (Phase I SBIR)
  - Integrates FDM head derived from AMF, wire and arc metal deposition system,
  - Ultra Tech Ultrasonic Additive Manufacturing (UAM) system (Phase I SBIR)
  - Uses sound waves to consolidate layers of metal from foil feedstock
- Tethers Unlimited MAMBA (Metal Advanced Manufacturing Bot-Assisted Assembly) (Phase I SBIR)
  - Builds on ReFabricator recycling process
- Techshot, Inc. SIMPLE (Sintered Inductive Metal Printer with Laser Exposure) (Phase II SBIR)
  - AM process with metal wire feedstock, inductive heating, and a low-powered laser



Illustration of Vulcan Exterior Unit (image courtesy of Made in Space)

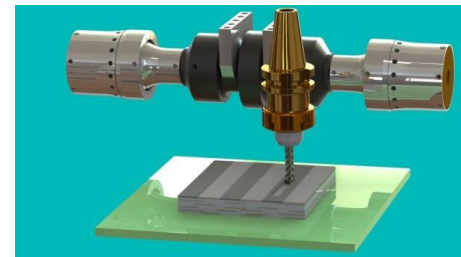
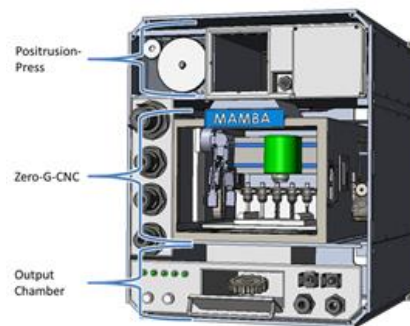
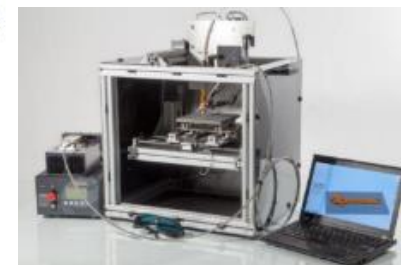


Illustration of UAM process (image courtesy of Ultra Tech)



Tethers Unlimited MAMBA concept. Image courtesy of Tethers Unlimited.



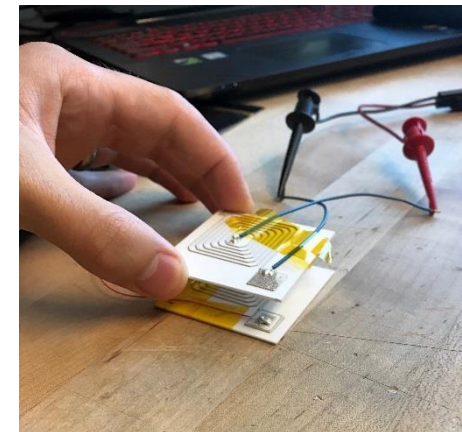
Techshot's SIMPLE, a small metal printer developed under a Phase I SBIR. Image courtesy of Techshot.



- Evaluating technologies to enable multi-material, digital manufacturing of components
- Development of additively manufactured wireless sensor archetype (MSFC)
  - Printed RLC circuit with coupled antenna
  - Capacitive sensing element is pressure, temperature, or otherwise environmentally sensitive material developed at MSFC
- Design of pressure switch for urine processor assembly (UPA)
  - Existing pressure switch has had several failures due to manufacturing flaw in metal diaphragm
  - In additive design, switching is accomplished via a pressure sensitive material
- Miniaturization and adaptation of printable electronics for microgravity environment will continue through two Phase 1 contracts awarded under SBIR subtopic In-Space Manufacturing of Electronics and Avionics
  - Techshot, Inc. (STEPS – Software and Tools for Electronics Printing in Space)
  - Optomec working on miniaturization of patented Aerosol Jet technology



MSFC nScript multimaterial printer  
(4 heads and pick and place capability)

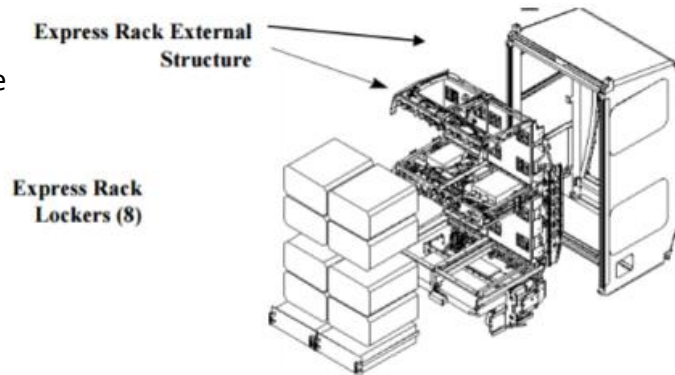


Printed wireless humidity sensor  
(wires attached for characterization purposes)

## Typical EXPRESS Rack structure

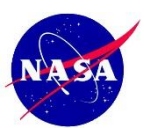
Power consumption for entire rack is limited to 2000 W

Payload mass limit for rack is less than 576 lbm



Threshold
The system should have the ability for on-demand manufacturing of multi-material components including metallics and polymers as a minimum.
The minimum build envelope shall be 6" x 6" x 6".
The system should include the capability for earth-based remote commanding for all nominal tasks.
The system should incorporate remote, ground-based commanding for part handling and removal in order to greatly reduce dependence on astronaut time.*
The system should incorporate in-line monitoring of quality control and post-build dimensional verification.

- NASA is evaluating proposals to provide a feasible design and demonstration of a first-generation multimaterial, multiprocess In-space Manufacturing Fabrication Laboratory for demonstration on the ISS
- Minimum target capabilities include:
  - Manufacturing of metallic components
  - Meet ISS EXPRESS Rack constraints for power and volume
  - Limit crew time
  - Incorporate remote and autonomous verification and validation of parts
- Phased approach
  - Phase A – scaleable ground-based prototype
  - Phase B – mature technologies to pre-flight deliverable
  - Phase C – flight demonstration to ISS



# In-space Robotic Manufacturing and Assembly (IRMA) Overview



*Concept by Made In Space*

## Archinaut

A Versatile In-Space Precision Manufacturing and Assembly System



*Concept by Space Systems/Loral*

## Dragonfly

On-Orbit Robotic Installation and Reconfiguration of Large Solid Radio Frequency (RF) Reflectors



*Concept by Orbital ATK*

## CIRAS

A Commercial Infrastructure for Robotic Assembly and Services

### Tipping Point Objective

A ground demonstration of additive manufacturing of extended structures and assembly of those structures in a relevant space environment.

A ground demonstration of robotic assembly interfaces and additive manufacture of antenna support structures meeting EHF performance requirements.

A ground demonstration of reversible and repeatable robotic joining methods for mechanical and electrical connections feasible for multiple space assembly geometries.

### Team

Made In Space, Northrop Grumman Corp., Oceaneering Space Systems, Ames Research Center

Space Systems/Loral, Langley Research Center, Ames Research Center, Tethers Unlimited, MDA US & Brampton

Orbital ATK, Glenn Research Center, Langley Research Center, Naval Research Laboratory

# Additive Construction Dual Use Technology Projects For Planetary and Terrestrial Applications

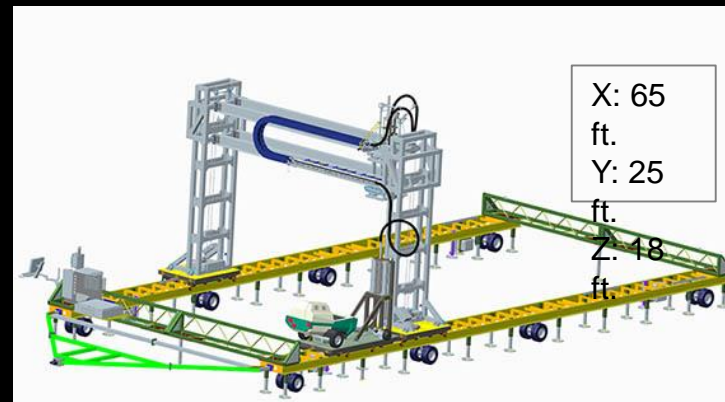


**Additive  
Construction with  
Mobile Emplacement  
(ACME)  
NASA**



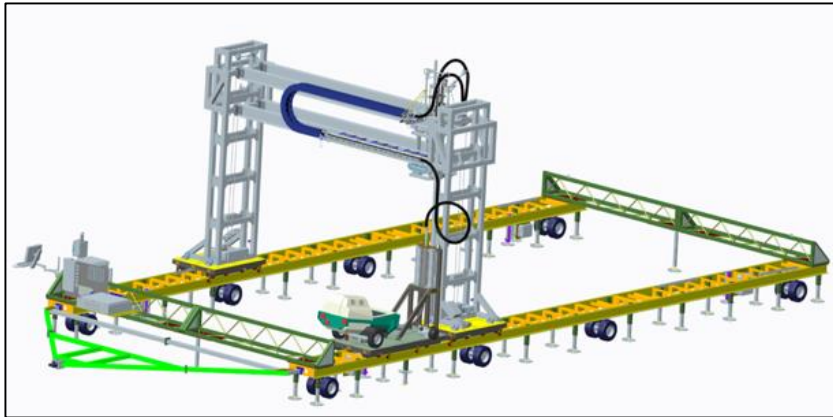
**Shared Vision: Capability to print custom-designed  
expeditionary structures on-demand, in the field,  
using locally available materials.**

**Automated Construction of  
Expeditionary Structures  
(ACES)  
Construction Engineering  
Research Laboratory - Engineer  
Research and Development  
Center  
(CERL – ERDC)**



**B-hut  
(guard shack)  
16' x 32' x 10'**





Model of ACES-3 Gantry System



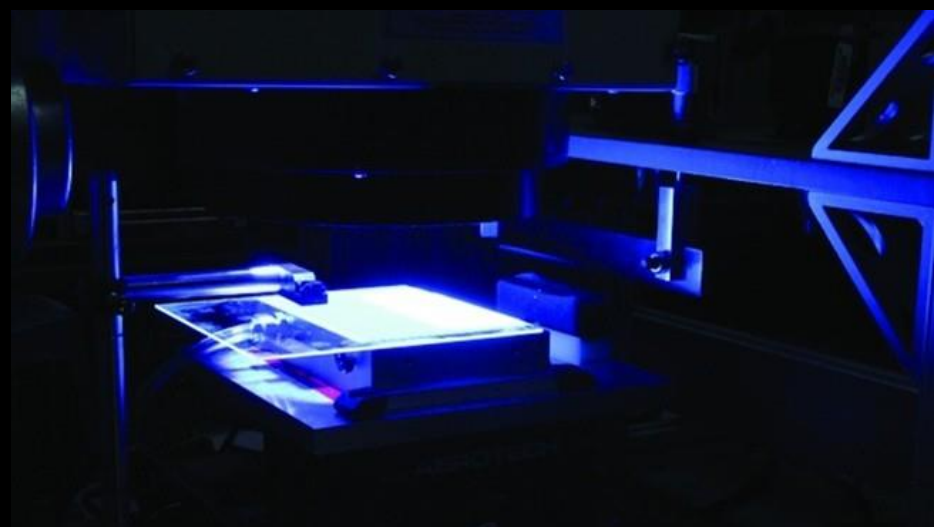
ACES-3 System in Champaign, IL



ACES-3 in Champaign, IL, aerial view



KSC Material Delivery System



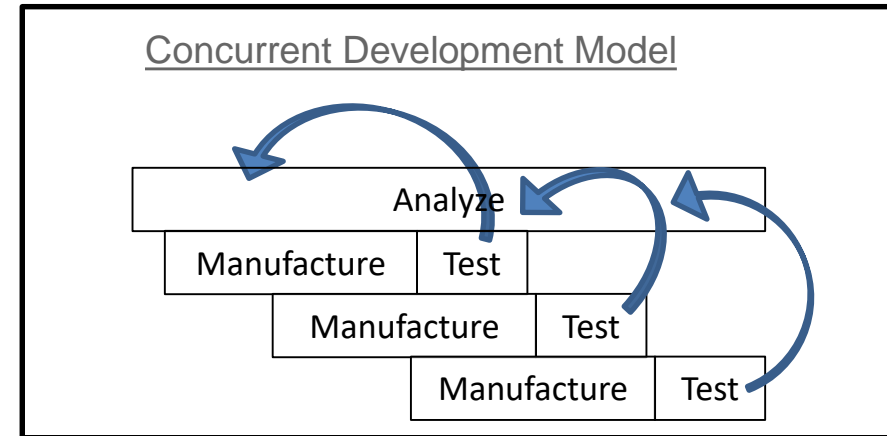
# Additive Manufacturing

at Marshall Space Flight Center

**Additive Manufacturing Development for  
Liquid Rocket Engine Space Flight Hardware**

## Strategic Vision:

- Defining the Development Philosophy of the Future
- Building Foundational Industrial Base
- Building Experience
- Developing “Smart Buyers” to enable Commercial Partners
- Enabling and Developing Revolutionary Technology
- SLM Material Property Data, Technology, and Testbed shared with US Industry

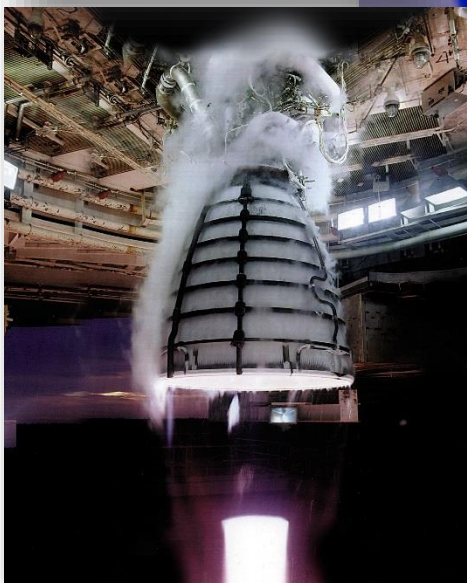


## Focus Areas:

- SLS Core Stage Engine, RS-25
  - Process development and characterization
  - Material property characterization and database development (Inconel 718)
  - Pathfinder component fabrication
- In Space Propulsion Class Additive Manufacturing Demonstrator Engine (AMDE)
  - Chambers
  - Valves
  - Injectors
  - Turbomachinery
  - Nozzles
- Small Satellite Propulsion Components



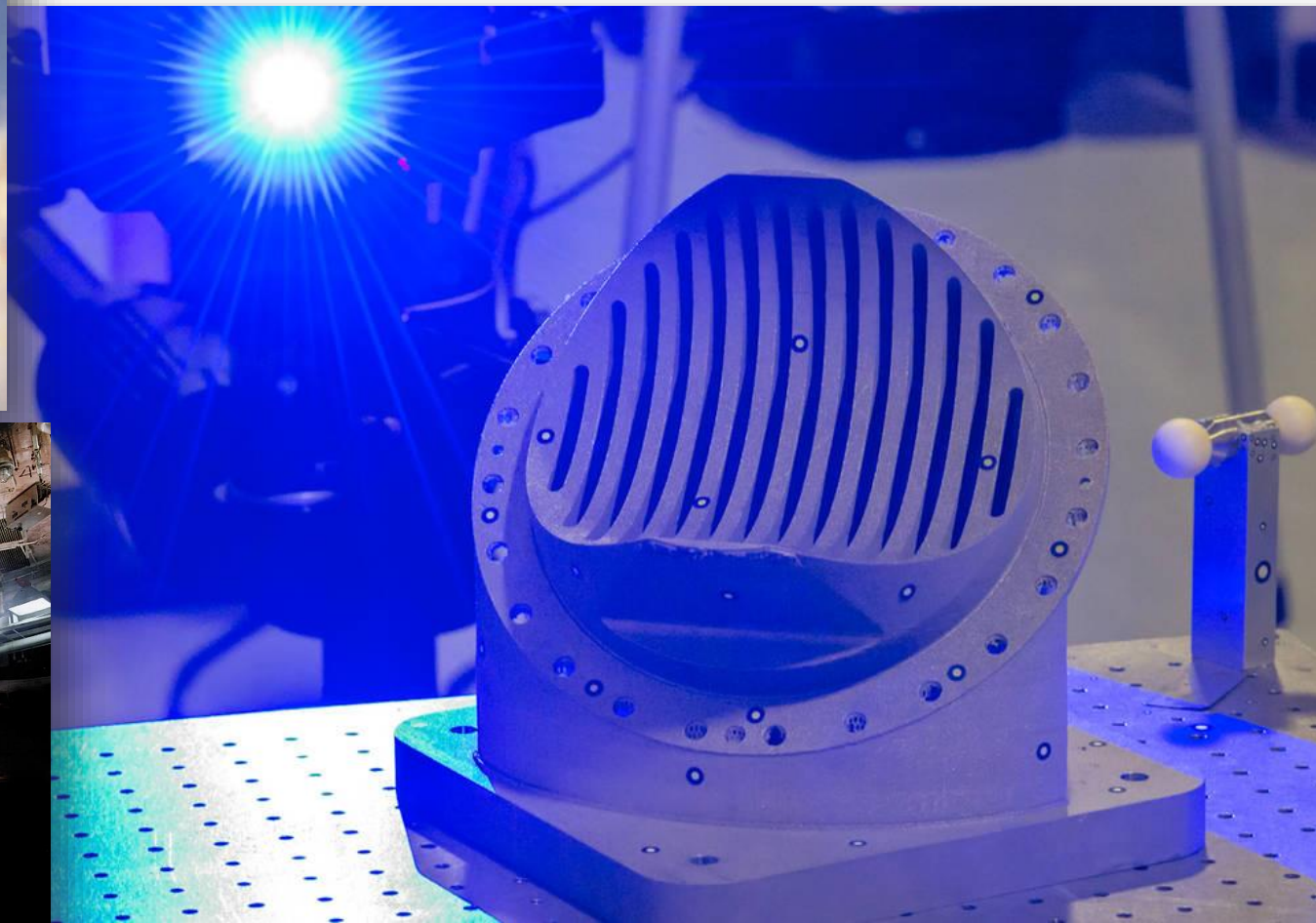
# SLS Program / RS-25 Engine Example Pogo Z-Baffle



## Inconel 718

Used existing design with additive manufacturing to reduce complexity from 127 welds to 4 welds

- 1 of 35 part opportunities being considered for RS25 engine





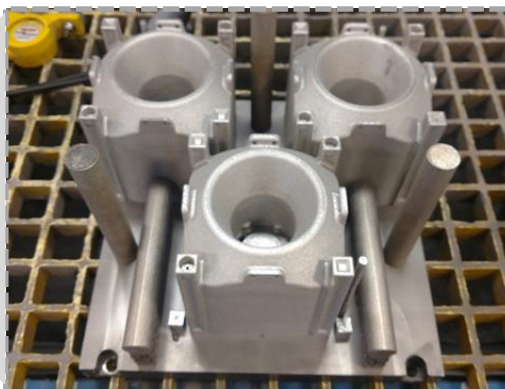


CubeSat cuboidal tank design:


- Topology optimized
- Printed
- Successfully hydrostatic proof tested



- Topology optimized monopropellant thruster thermal standoffs, injectors
- Reactors with integrated flow passages for small spacecraft
- CubeSat propulsion systems (1 Newton)



Detailed design and fabrication of 3U and 6U CubeSat Propulsion Modules




Oxidizer Turbine Bypass

Main Oxidizer Valve (MOV)

Main Fuel Valve/Coolant Control

### Valve Development



100 lb LOX Propane

1.2K LOX Hydrogen

20K AMDE Lox Hydrogen

4K Methane

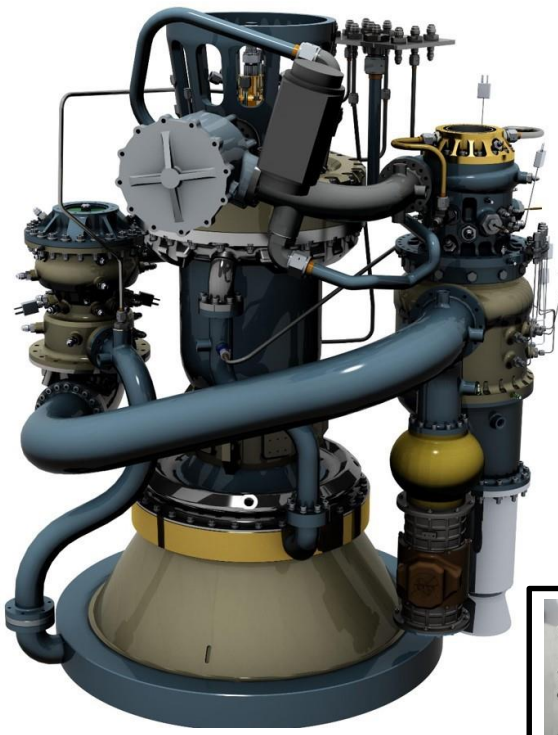

20K AMDE Lox Hydrogen

35k Methane GG

### Injector Development



### Copper Main Combustion Chamber Development

Pump Housing

Turbine Housing

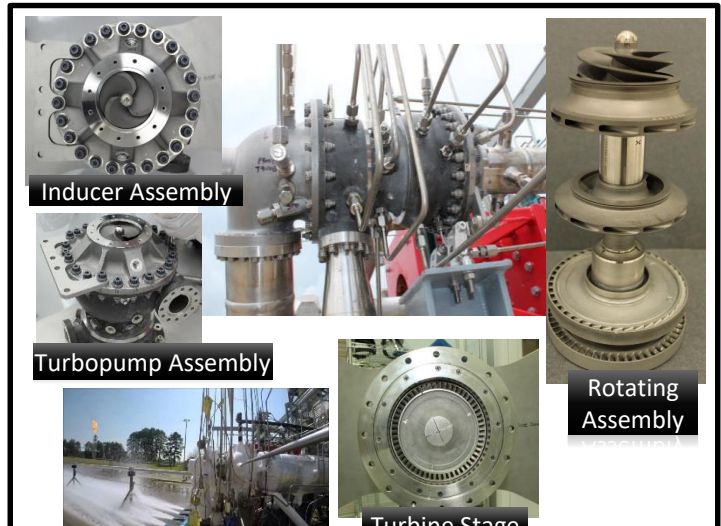
Shaft Baffle

Impeller

Turbine

Stator

### Liquid Oxygen Turbopump Development



Inducer Assembly

Turbopump Assembly

Rotating Assembly

Turbine Stage

### Fuel Turbopump Development

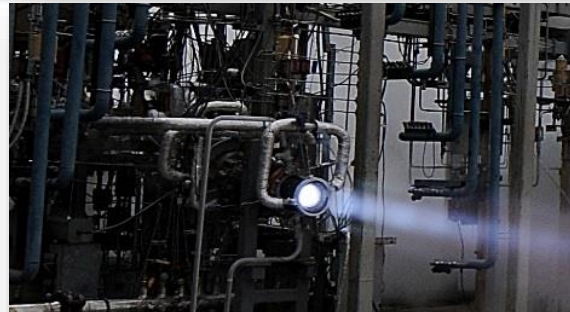




GRCop-84 3D printing process developed at NASA and infused into industry



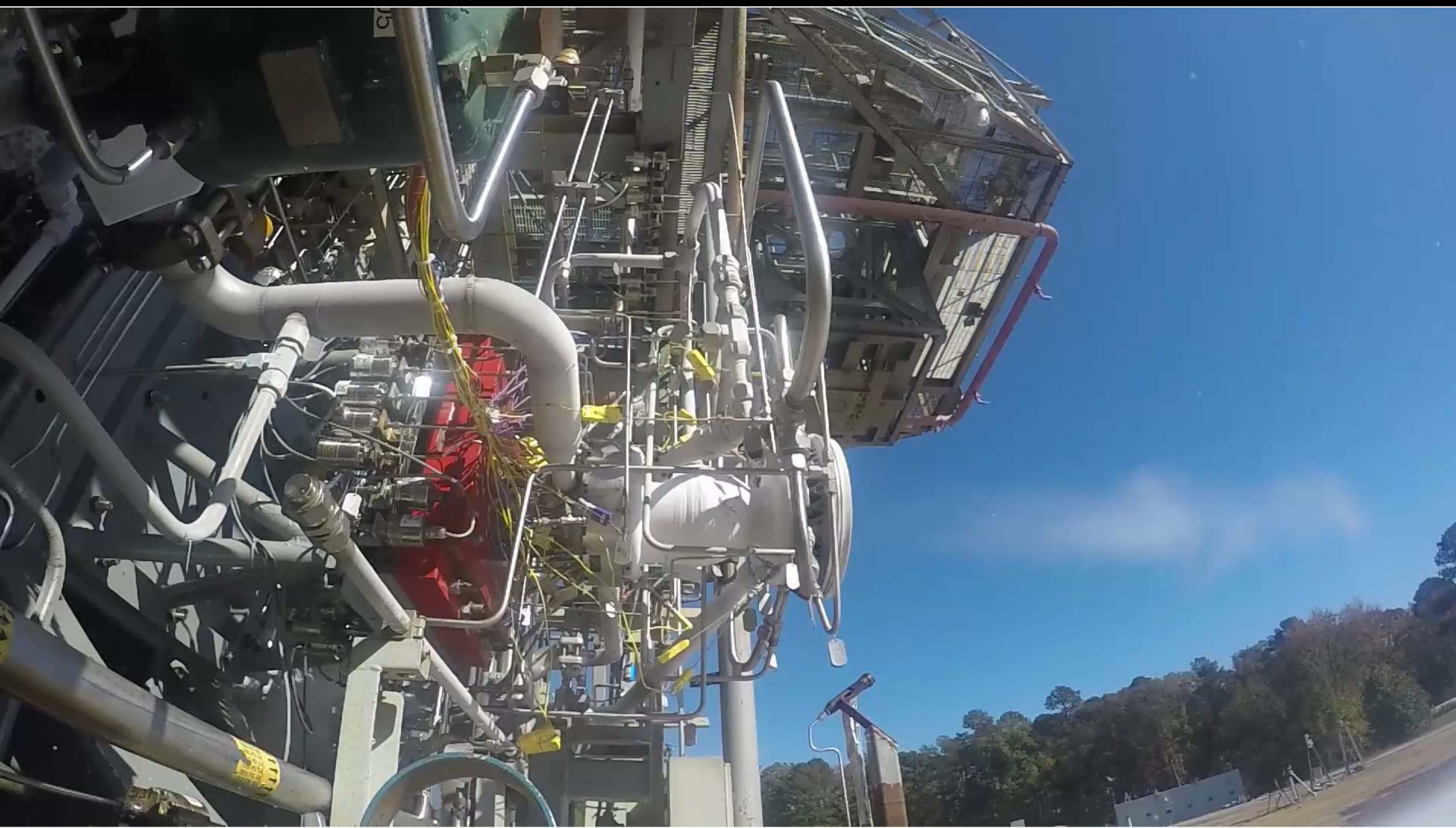
GRCop-84 AM Chamber Accumulated **6000 sec** hot-fire time at full power with no issues



LOX/Methane Testing of 3D-Printed Chamber  
Methane Cooled, tested full power



First successful Lox/Hydrogen hot fire test of a regen-cooled GRCop-84 3D printed MCC with an integral Electron Beam Free Form Fabrication (EBF3) deposited nickel superalloy jacket.







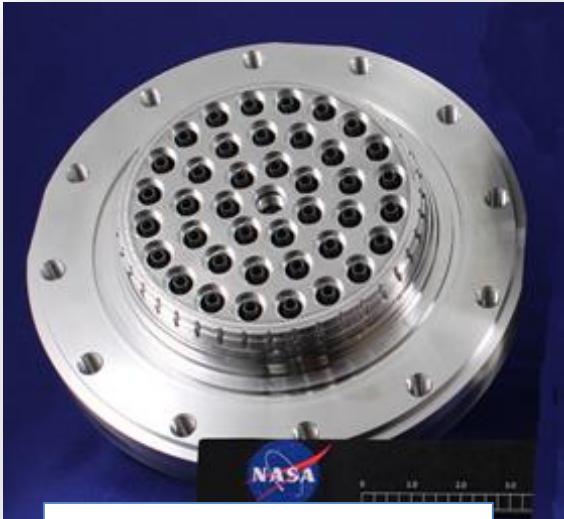
100# LOX Propane  
Injector Built 2012  
**Tested Nov 2013**



1.2K LOX Hydrogen  
First Tested June 2013  
**>7000 sec hotfire**



20K LPS Subscale Tested Aug 2013  
**(3) Subscale Injectors Tested**



Methane 4K Injector  
Printed manifolds  
**Tested Sept 2015**



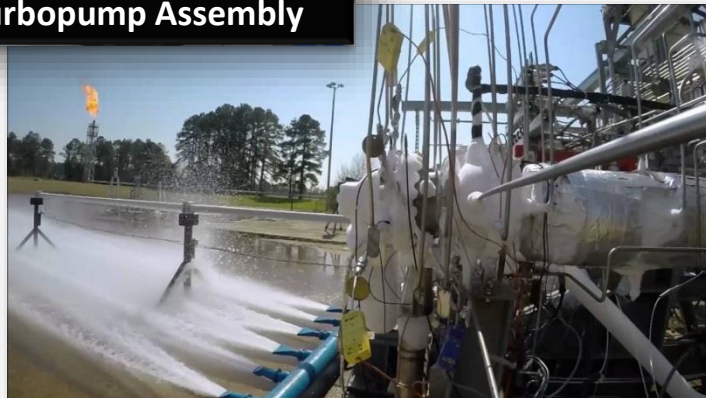
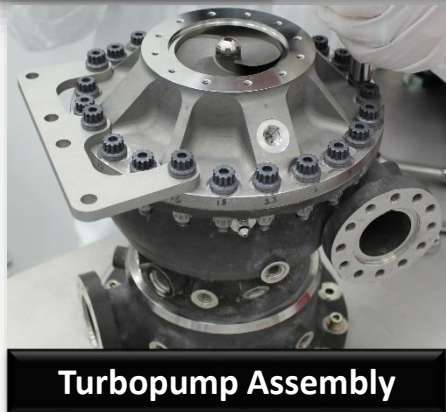
LPS 35K Injector  
Welded Manifolds  
**Tested Nov 2015**



CH4 Gas Generator Injector  
**Testing Summer 2017**

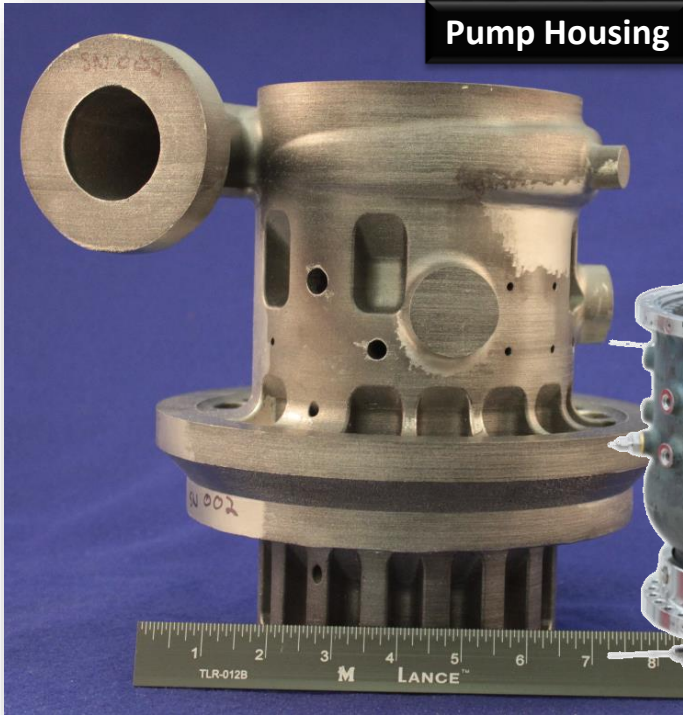
Ref: Brad Bullard Sandy Elam Greene

# Fuel Turbopump Development and Test





**Pump Housing**



**Turbine Housing**



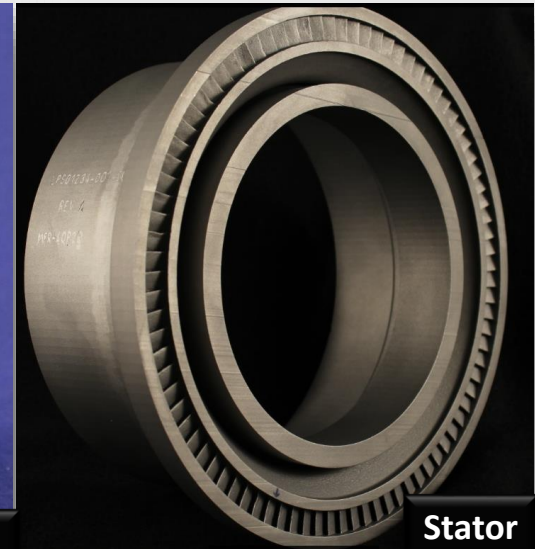
**Shaft Baffle**



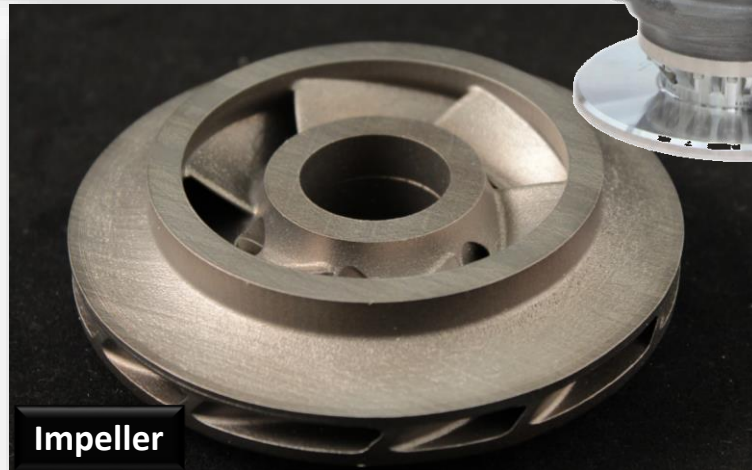
**Turbine Blades**



**Stator**

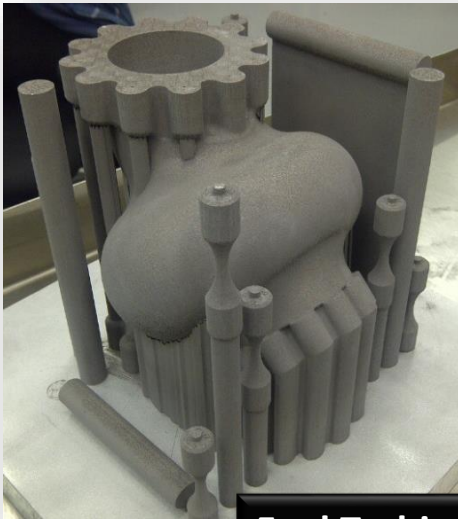


**Impeller**

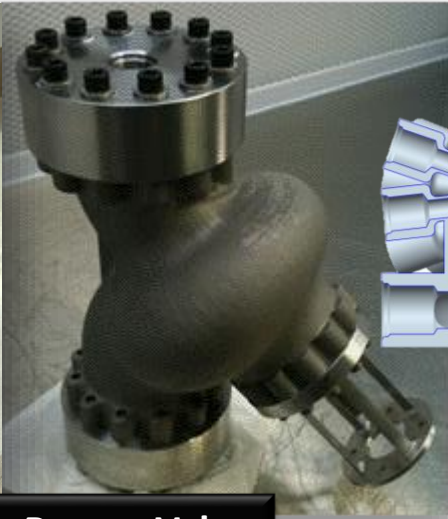


Ref: Derek O'Neal / NASA MSFC

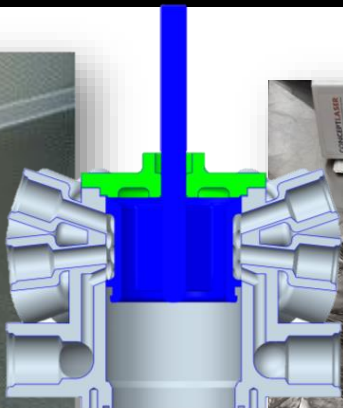




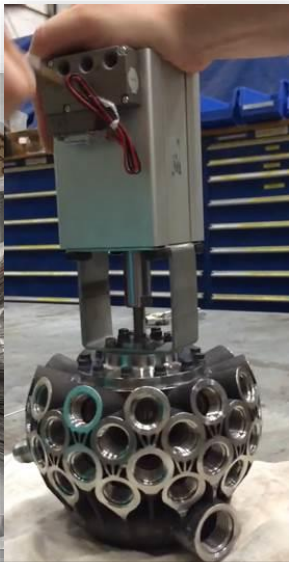
**Fuel Turbine Bypass Valve**



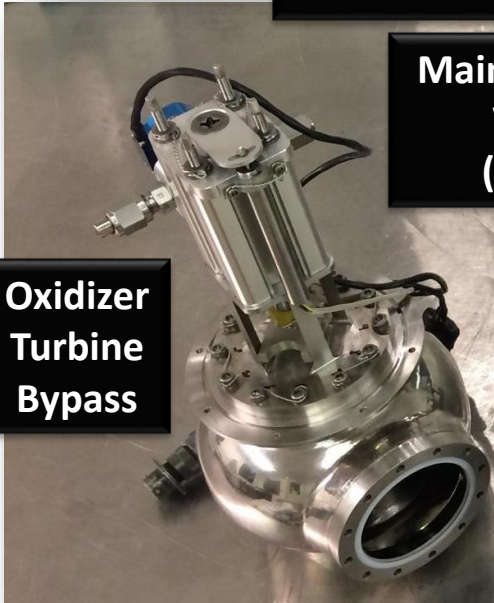
**Main Oxidizer Valve (MOV)**



**Aerospike Engine Multi-Port Valve**



**Oxidizer Turbine Bypass**



**Main Fuel Valve / Coolant Control Valve (MFV/CCV)**





# Large Scale Additive Deposition Nozzle Technology Development

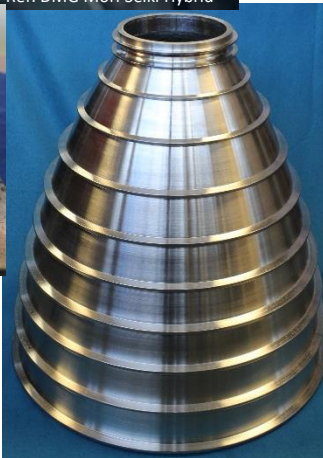
24+” Dia

**Large Scale Deposition:  
Blown Powder and Arc Deposition**



Ref: DMG Mori Seiki Hybrid

**Additive Wire-based Channel Closeout**



**Freeform AM Deposition with Integral Channels**



27” Dia

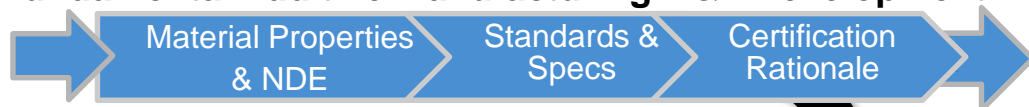


Morgan, K. L., Gradl, P., “Additive Manufacturing Overview: Recent Propulsion Applications,” Additive Manufacturing for Defense and Government Conference, July 2017.

Gradl, P. “Rapid Fabrication Techniques for Liquid Rocket Channel Wall Nozzles.” AIAA-2016-4771, Paper presented at 52nd AIAA/SAE/ASEE Joint Propulsion Conference, July 27, 2016. Salt Lake City, UT.

Gradl, P.R., Brandsmeier, W. Alberts, D., Walker, B., Schneider, J.A. Manufacturing Process Developments for Large Scale Regeneratively-cooled Channel Wall Rocket Nozzles. Paper presented at 63rd JANNAF Propulsion Meeting/9th Liquid Propulsion Subcommittee, December 5-9, 2016. Phoenix, AZ.

## Fundamental Additive Manufacturing M&P Development



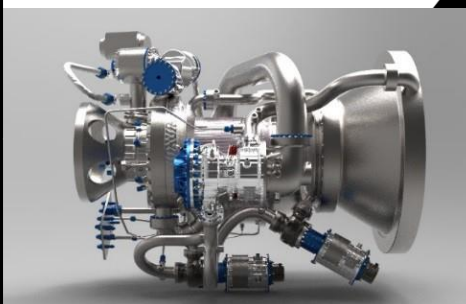
### Lean Component Development



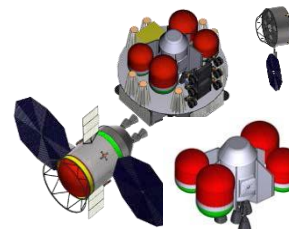
### Component Relevant Environment Testing



### AMDE Prototype Engine



### Methane Propulsion Systems



### CCP



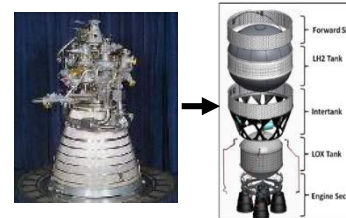
### Nuclear Thermal Propulsion



### SLS: RS-25

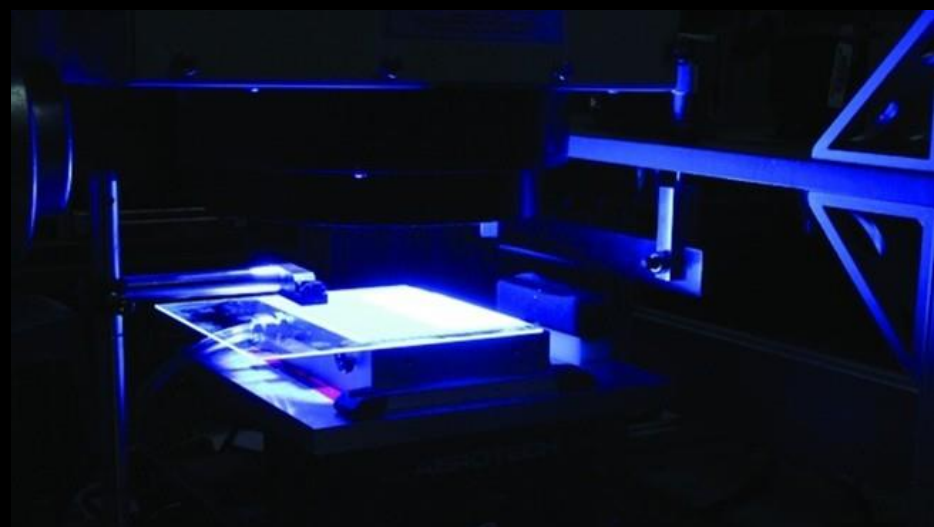


### Upper Stage Engine



Building Foundational Additive Manufacturing Industrial Base





# Additive Manufacturing

at Marshall Space Flight Center

## MSFC Standard and Specification for Additively Manufactured Spaceflight Hardware



## Exploration Systems Development ORION and SLS



## Commercial Crew Program (CCP) DRAGON V2



NASA Exploration Programs and Program Partners have embraced AM for its affordability, shorter manufacturing times, and flexible design solutions.

## ***NASA cannot wait for national Standard Development Organizations to issue AM standards.***

- Partners in crewed spaceflight programs (Commercial Crew, SLS and Orion) are actively developing AM parts
- In response to request by Commercial Crew Program (CCP), MSFC AM Standard drafted in summer 2015.
- Draft standard completed extensive peer review in Jan 2016.
- **Standard methodology adopted by CCP, SLS, and Orion.**
- Continuing to participate with standards organizations and other certifying Agencies.
- Goal is to incorporate AM requirements at an appropriate level in Agency standards and/or specifications.



MSFC Standard and Specification  
Release Date: October 18, 2018

Standardization is needed for consistent evaluation of AM processes and parts in critical applications.

# Summary: In Space Manufacturing Applications

## Conclusions from Systems Analysis of ISM Utilization for the Evolvable Mars Campaign: Why ISM

- Current maintenance logistics strategy will not be effective for deep space missions
- ISM has the potential to significantly reduce maintenance logistics mass requirements by enabling material commonality and the possibility of material recycling and ISRU for spares
- ISM should be considered and developed in parallel with the systems design

NASA is actively working to develop ISM capabilities:

- **Within Pressurized Volume:** Reduce the logistics challenges and keep astronauts safe and healthy in transit and on extraterrestrial surfaces. ISS is a critical testbed.
- **External/Free Space - IRMA:** Develop new commercial capabilities for robotic spacecraft construction, repair, refurbishment, and repurposing in LEO
- **Extraterrestrial Surfaces - Additive Construction:** Enable infrastructure to be robotically constructed pre- or post-arrival of astronauts on the extraterrestrial surface, whether that be the Moon or Mars.

To achieve functional capability supporting the Exploration timeline, ISM must work with Exploration systems designers now to identify high-value application areas and influence process.



# Summary: Space Propulsion System Applications

MSFC has made a major thrust in the application of AM for development of liquid rocket engines ranging from the Space Launch System Core Stage RS-25 engine, to In-Space Class prototype engines, to Cubesat propulsion systems.

- Process development, material property characterization, and component fabrication trials for RS-25 Inconel 718 material applications.
- New design and development philosophy successfully exercised to build AMDE, a prototype in-space class engine incorporating additive manufacturing to reduce costs, schedule and parts counts.
  - Designed and additively manufactured > 150 rocket engine parts in 2.5 years
  - Encompassed every major component and assembly of the engine
  - Developed and demonstrated capability to additively manufacture with copper.
  - Data, expertise, and testbed shared with industry for current/future developments
- Capabilities developed through AMDE experience have been applied to small satellite propulsion systems components design and development

NASA MSFC created a Standard and Specification for AM Spaceflight Hardware in response to near-term programmatic demand.

- Shaped the approach to additive parts for current human-rated space flight programs through early release of Draft Quality Standard approach.
- Standard and Specification provide a framework for consistent evaluation of AM Laser Powder Bed Fusion processes, properties, and components.

